

THERMAL RESPONSE TEST –POWER INJECTION DEPENDENCE

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1. BACKGROUND

Thermal response test (TRT) is an established method to determine design parameters for borehole heat exchanger (BHE) systems; borehole thermal resistance and effective ground thermal conductivity. Most commonly, these tests are performed with heat injection, using the same assumed power level as the planned BHE system. For a thorough description of TRT and current activities around the world, see Gehlin (2002) or Gehlin and Spitler (2002).

It has been shown that groundwater movement may influence the test result, e.g. by Sanner et al. (2000). Several investigations of the influence of regional groundwater flow on ground thermal conductivity have been performed. Chiasson et al. (2000) conducted a numerical investigation which concluded that regional groundwater flow only influenced the heat transfer in BHEs for certain geohydrological conditions. An enhanced heat transfer was seen in grounds with high hydraulic conductivity, such as coarse-grained soils (sand and gravel) or formations with secondary porosities such as fractures.

This was further studied by Witte (2001), who performed measurements and conducted a numerical study of ground consisting of a clayey cover layer and a water bearing formation consisting mainly of sand. He showed that even small groundwater flow resulted in a higher estimation value of the ground thermal conductivity. Gehlin and Hellström (2003a) used three different model approaches to investigate the influence from regional groundwater flow; continuous porous media, fracture zone with a homogenous porosity and vertical fracture. They showed that relatively low flow rates in fractures may significantly enhance the heat transfer even though a model simulating the ground as a continuous porous media using Darcy's equation suggested otherwise.

In Scandinavia, groundwater is most commonly used to fill the volume between collector and borehole wall. Gehlin et al. (2003) investigated how thermally induced fracture flow may occur in boreholes with suitable connecting fractures. This thermosiphon effect was a result of volumetric expansion of the heated borehole water. Heated borehole water flowed out of the borehole through a fracture at the top while colder groundwater entered the borehole at the bottom, due to the arisen pressure differences. It was shown that heat transfer in and around the borehole was increased with this flow.

All these investigations were made for special geohydrological conditions with fairly high porosity or suitable fractures in the ground. However, for TRT in groundwater-filled boreholes there will always be an influence on heat transfer from buoyancy flow inside the borehole, which occurs independently of fractures in the ground. This is due to the arisen temperature gradient in the borehole and the resulting density differences in the water. The induced buoyancy-driven flow (natural convection) will enhance the heat transfer from collector to borehole wall. This reduces the borehole resistance compared to stagnant water. The flow rates in the borehole water and thereby heat transfer will depend on the temperature and the temperature gradient inside the borehole. This paper investigates the change in borehole thermal resistance due to injection rate for thermal response tests. It also shows how this affects the calculated total borehole length for an example borehole system.

2. TEDHC – A SWEDISH THERMAL RESPONSE TEST RIG

In 2004, Luleå University of Technology (LTU) built a thermal response test rig, TEDhc, which may both inject and extract heat (heating and cooling mode). A similar design has been built by Groenholland and is described e.g. in Witte (2001). This test rig is used to investigate groundwater influence on borehole heat exchangers and response tests. Several heat injection tests with different power injection rates have been performed to investigate the borehole thermal resistance dependency of the injection rate in a groundwater-filled borehole.



Figure 1: The new Swedish TRT equipment, TEDhc

The TEDhc rig consists of two separate systems; the heating and the cooling system. In heating mode, a 3 – 12 kW stepwise adjustable electrical heater supplies the injection energy. The heat carrier fluid is circulated through the test equipment and borehole collector by a 3 kW variable pump. Ambient air temperature, ingoing and outgoing fluid temperatures, rig reference temperature, flow velocity and electrical power demand are measured and recorded during the test. In cooling mode, a fluid-to-air heat pump connected to a buffer tank will supply the circulating heat carrier with constant cooling power. Unfortunately some regulation problem has so far prevented tests in cooling mode.

A TEDhc test is conducted by injecting constant power for approximately 72 h with the thermal response recorded every 5 – 10 minutes. The undisturbed ground temperature and BHE details such as groundwater-filled borehole length, borehole and collector diameter and heat carrier fluid properties are required for the evaluation. A numerically calculated thermal response is then least square approximated with the measured response to get the effective ground thermal conductivity, λ_e , and the borehole thermal resistance, R_b . The numerical model is a 2D axisymmetric model (Hellström, 2001) similar to the numerical model described in Gehlin and Hellström (2003b).

3. HEAT INJECTION TESTS

The arisen natural convective flow (buoyancy and thermosiphon) in and around a BHE depends on temperature gradients, fractures and borehole heat exchanger dimensions. The convective heat transfer may be studied by performing several injection tests in the same borehole, with different power rates. The data is then evaluated to investigate influence of groundwater movements on the ground thermal conductivity and borehole thermal resistance for the different power rates. In this study, the borehole is situated in crystalline bedrock with no or few fractures. Performed investigations for the ground thermal conductivity show no influence from regional or induced groundwater movements. In the groundwater-filled borehole, however, the induced buoyancy-driven flow enhances the heat transfer which decreases the borehole thermal resistance.

Four different heat injection tests were performed in a borehole heat exchanger at LTU. The borehole is 150 m deep and has two DN40PN6 U-pipe installed; one 75 m deep and one 150 m deep. Heat injection thermal response test measurements were performed on the 75 m U-pipe. Each test consists of one or more power level periods to investigate the influence from buoyancy-driven flow on the heat transfer.

The groundwater influence on the effective ground thermal conductivity, λ_e , depends on site-specific fractures and hydraulic gradient. Hence this must be investigated for each new measurement location. A conventional method is to analyse the measurement data by including more and more data, i.e. least square approximation over longer and longer measurement times. If the estimated ground thermal conductivity does not change with time, groundwater influence may be disregarded (the method is described in e.g. Witte, 2001). Such investigations of the measurement data indicate little or no groundwater influence on the effective ground thermal conductivity. Each measurement is therefore evaluated with one value of ground thermal conductivity but separate borehole thermal resistance for each power rate.

In Table 1, the heating power and duration time for each measurement are accounted for. The resulting evaluated design parameters, effective ground thermal conductivity, λ_e , and borehole thermal resistance R_b are also shown. Some periods had only the circulation pump running during the tests. The electrical power (driving energy of the pump) is then approximately 0.5 kW, of which some is heating the circulating heat carrier fluid. In the M4 measurement the result for the second circulation pump period is evaluated using only 53 h instead of approximately 72 h, which results in some uncertainties for those values.

Table 1: Mean power and test time for each power level together with evaluated parameters, bedrock thermal conductivity and borehole thermal resistance, for each TRT measurement M1-M4.

Measurement	Start date	Mean power load [kW]	Duration [h]	λ_e [W/m,K]	R_b [Km/W]
M1	050329	6	70	3.4	0.065
M2	050420	Circulation pump	26	3.2	0.069
		3	98		
		6	99	3.2	0.059
		Circulation pump	71	3.2	0.104
M3	050801	Circulation pump	23	3.5	0.067
		6	72		
		3	96	3.5	0.077
M4	050921	Circulation pump	27	3.3	0.065
		6	116		
		Circulation pump	53	3.3	0.096
		3	120	3.3	0.073
		Circulation pump	23	3.3	0.073
3	307				

The buoyancy flow in the groundwater-filled borehole will depend on density gradient between heat carrier fluid and borehole wall. A higher injection rate results in larger temperature difference between pipe walls and borehole wall. The resulting larger density difference induces higher flow velocities inside the borehole water which will enhance the heat transfer. A higher injection rate will therefore give a smaller borehole thermal resistance. The density-temperature relationship for water is not linear; the density gradient is therefore also dependent on the actual temperatures in the borehole. In the investigated temperature interval (10 - 23°C) a temperature difference of one degree results in a larger density difference for a higher water temperature than for a lower water temperature. A higher borehole water temperature will therefore result in a lower borehole thermal resistance.

Borehole heat exchanger systems may be used for a wide range of temperature levels. Heat carrier fluid temperatures in the range of -5 to 20°C are common in Sweden for heat injection/extraction systems. For storage systems the heat carrier temperature could be up to approximately 80°C. Therefore it is of interest to investigate the influence from buoyancy flow on the borehole thermal resistance in a larger temperature interval than the presented measurements.

Previously, high temperature measurements have not been conducted on normal length BHEs (100-200 m). However, a laboratory study of the heat transfer in a water-filled borehole heat exchanger was conducted in 1999 by Kjellsson and Hellström. The test equipment represented a 3 m long borehole heat exchanger with a diameter of 0.1036 m. Outside was a steel cylinder with a diameter of 0.4 m, containing a mixture of fine sand and a water-antifreeze fluid which represented the bedrock. A cryostat-controlled circulating fluid maintained the cylinder at a certain temperature, T_c . Several injection rates and cryostat temperatures were used to investigate the heat transfer in the borehole water. From these experiments it is seen that the resulting borehole thermal resistance are mostly dependent on the temperature level, i.e. the mean water temperature inside the borehole.

In Figure 2, borehole thermal resistance, R_b , is plotted against the mean fluid temperature of the heat carrier fluid for the TED measurements and for the experiment by Kjellsson and Hellström. The mean fluid temperature is calculated for the TED measurement as mean value of inlet and outlet temperature during the third day at each power level. For the experiment, stated values from the report are used. The mean fluid temperature will be a few degrees higher than the borehole water temperature due to the resistance of U-pipe material.

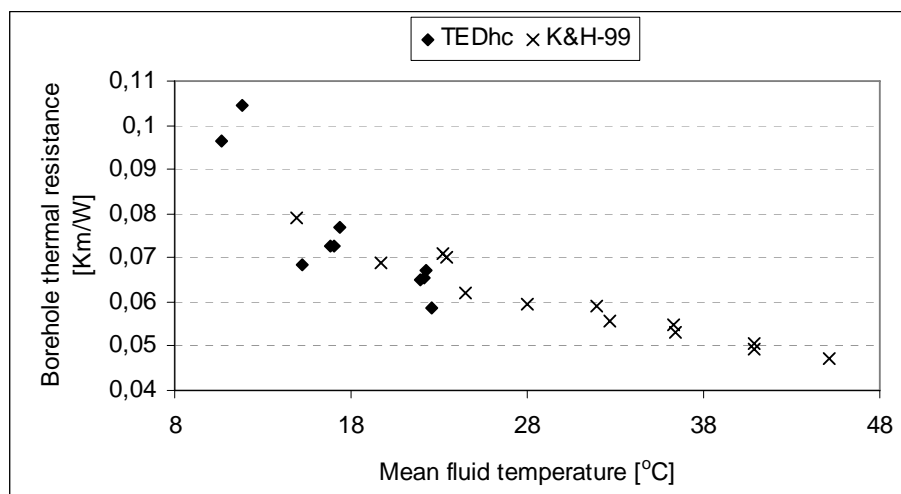


Figure 2: Borehole thermal resistance, R_b [m,K/W], plotted against mean fluid temperature for TED measurements and for experiment from 1999 (K&H-99).

The evaluated effective ground thermal conductivity differs in the four measurements (Table 1). Spitler et al. (2000) and Witte et al. (2002) showed that uncertainties in input data during the evaluation result in uncertainties in the estimations with approximately 8 - 10 % for their equipments. Sources of error are e.g. uncertainties in determined value for undisturbed ground temperature and heat losses or model approximations. By using an example system the uncertainty in evaluated design parameters may be investigated. The example system is described in section 4. Table 2 shows calculated required total borehole lengths for the system using the evaluated parameters for the different 6 kW power rate periods. The maximum difference is approximately 60 m between the M3 and M4 measurement, which corresponds to a third of a borehole.

Table 2: Result for the four different 6 kW periods. For each evaluated value a total borehole length is calculated for the example system described in section 4.

Measurement	λ_e [W/m,K]	R_b [Km/W]	Tot. borehole length
M1	3.4	0.065	2611
M2	3.2	0.059	2647
M3	3.5	0.067	2590
M4	3.3	0.065	2652

4. DESIGN OF BOREHOLE HEAT EXCHANGER SYSTEM

To see the effect of the borehole thermal resistance on a borehole heat exchanger system, an example system was constructed in the design program EED [Earth Energy Designer 2.0]. The system consists of 15 boreholes in a 5x6 U-configuration in granite bedrock, located in Luleå, Sweden. The spacing between two boreholes is 14 m and they are fitted with DN40PN6 single U-pipes. The system is used for both heat injection and extraction, with approximately 10 % of the total amount of heat extraction injected during the summer.

In Figure 3, the calculated total borehole length is shown for borehole thermal resistance between 0.05 Km/W and 0.1 Km/W. In summer time the system is used for heat injection. Common heat carrier temperature levels for cooling purpose are 17-18°C. In winter time heat extraction lowers the borehole temperature to around zero degrees. A system designed after a TRT measurement with heat injection may result in an evaluated borehole thermal resistance of 0.07 Km/W. This corresponds to a total borehole length of 2660 m for the example system. During the winter the borehole thermal resistance then increases to 0.1 or more (unless it freezes) which gives a total borehole length of 2890 m. This will result in a less efficient BHE system than calculated if the system is designed for a resistance of 0.07 m the year round. It is therefore desirable that transient borehole thermal resistance is included in design and analyses programs for borehole heat exchanger system and thermal response test or that convective heat transfer models are incorporated in these programs.

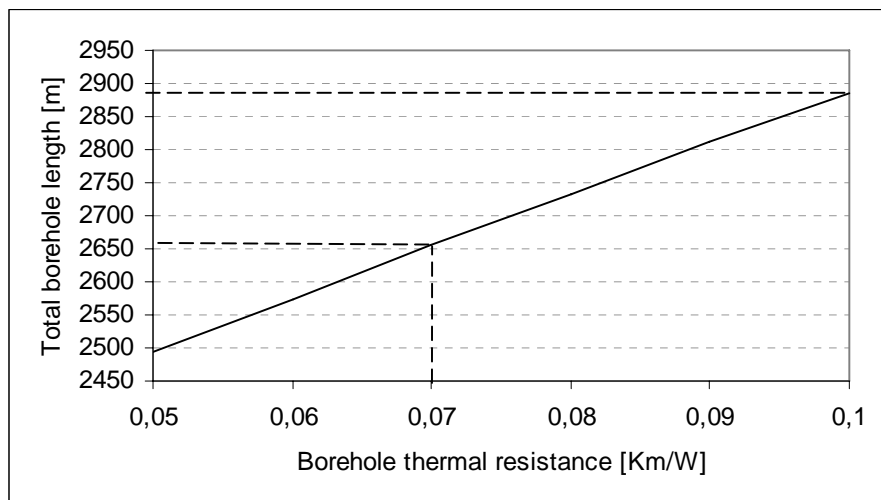


Figure 3: Calculated total borehole length for example BHE system for different borehole thermal resistance. The dotted lines shows the calculated borehole length for a fluid temperature ~18°C ($R_b = 0.07$ Km/W) and 10°C or below ($R_b = 0.1$ Km/W) which corresponds to summer and winter time.

5. CONCLUSION AND FUTURE WORK

During operation of a borehole heat exchanger (BHE) system, temperature gradients are induced in and around the borehole. This results in a temperature-density driven flow that increases the heat transfer in the borehole. The buoyancy flow will depend on temperature gradient and temperature level in the BHE. A higher temperature in the borehole water decreases the borehole thermal resistance compared to a lower temperature.

BHE systems with differing temperature levels over the year require different design borehole thermal resistance during the different seasons for a correct design. Since today's BHE calculation programs do not include the convective heat flow or changing resistance over the year, the designer needs to consider this and do multiple designs. Nowadays when larger systems are getting more common it would be desirable to include the buoyancy flow in the design model and thermal response test (TRT) evaluation.

The presented results are part of an ongoing project to investigate groundwater influence on groundwater-filled borehole heat exchangers. Thermal response test will be performed with high temperature measurements, forced groundwater flow measurements and heat extraction measurements. The result from these measurements will be used to design a numerical model accounting for both the conductive and convective heat transfer in the BHE.

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